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Stress distribution in a pin-loaded metal plate with glued reinforcement plates.

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STRESS DISTRIBUTION IN A PIN-LOADED METAL PLATE WITH GLUED REINFORCEMENT PLATES

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PREFACE

Following World War II, the advent of the use of sandwich materials in the construction of aircraft presented many new problems to industry. The importance of this material was firmly established by the time Chance Vought Aircraft built the U.S. Navy model F7U airplane. This aircraft, a carrier based, jet propelled fighter, is the first American production model to feature the use of sandwich skin.

In spite of this, however, sandwich design theories are not as fully developed as those involving the use of more "conventional" materials. Therefore, Chance Vought was able, on being approached by the student, to suggest the problem that was investigated for this thesis. In addition, they very kindly supplied the glued panels from which the test specimens were made.

This thesis, then, presents the results of the study, which was carried out during the 1951-52 school year at the University of Minnesota, Minneapolis, Minnesota.

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SUMMARY

This thesis presents the results of an investigation of one theory concerning the stress distribution in a pin-loaded metal plate with glued reinforcement plates. The theory itself was developed as an aid in finding shear stresses in the glue.

Five aluminum plates of the type used in aircraft construction, were tested in tension. Each plate was loaded at one end by a uniform load, and near the other end by a one inch diameter pin. The location of the pin was the variable from plate to plate.

The results indicated that the proposed theory was not suitable, because the loading for which the theory was developed was sufficiently different from the actual loading conditions.

Wide variations in strains produced by hole and pin combinations that were apparently the same, indicate that it may not be accurate to assume that pin or bolt bearing is truly uniform. Though this is a by-product of the present investigation, it is felt that further study along these lines is warranted.

INTRODUCTION

This research was suggested by the requirements resulting from the use of sandwich material in the construction of the newer military aircraft. The test specimens used were not sandwich materials, however, and the following is presented in order to explain the choice of test materials, and the applicability of the results to the design of fittings and attachments for sandwich materials.

The usual design of a sandwich panel to which bolts or rivets are attached involves the use of a hardwood insert and bonded metal doublers. The insert supplies resistance to transverse shear and crushing forces, and the doublers increase bearing strength. An example of one type of fitting is illustrated as Figure 1. An applied load transfers from the bolt or rivet to the doublers and the sandwich facings. The facings must take all of the load beyond the doublers, and the portion of the load that is introduced into the doublers must be transferred through the adhesive into the facings.

The strength of the fitting attachment depends upon the strength of the bond between the facing and the doubler. Thus, it is desirable to know the distribution of stresses within the bonding, in order to compare those stresses with

the shear strength of the adhesive. With this information, it will be possible to make the best use of bonding material and to design attachments most efficiently.

In the design of sandwich parts, the core, whether it is of balsa, or of one of the many other commonly used materials, is considered to offer no tensile strength in a direction parallel to the plane of the facings. Since this investigation was concerned only with those forces, the core could be of no value, and it was possible to treat the problem independently of any actual sandwich panels.

Figure 1 illustrates only one type of fitting that might be attached to a sandwich sheet. Another type, for example, might be an L-shaped bracket. In addition to the tensile forces mentioned above, such a bracket would apply a moment to the sandwich. This problem is no doubt of interest, but it would have complicated the present research beyond its intended scope.

For these reasons, a specimen such as that of Figure 2 was chosen. For the purposes of this analysis, Figure 2 can be treated as structurally the same as Figure 1. They are in fact the same, except that in the latter figure, the balsa core has been removed, and the two face plates have

been placed together to be considered as one. In each case, the load is applied by the pin to the doublers and face plates simultaneously. In each case, the load is finally transmitted from the doublers to the center piece.

THEORY

The theory presented in this section was not developed for the specific loading condition pictured in Figure 2. It was, instead, developed for the case of the standard glued lap joint shown in Figure 3(a).

It as assumed that, due to symmetry, the single lap joint of Figure 3(a) could be considered to be essentially the same as the double lap joint of Figure 3(b).

The application of the theory to the test panels will be discussed in the next section.

The following symbols will be used in the theoretical development:

A,B - constants of integration

c - a constant

E - Young's modulus of elasticity

G - shear modulus of the glue

L - lap length

N - total applied load

N_1 - load applied to sheet 1

N_2 - load applied to sheet 2

p_1 - force acting at any point, x, in sheet 1

p_2 - force acting at any point, x, in sheet 2

t - sheet thickness or glue thickness

u_1 - displacement of a particle in sheet 1

u_2 - displacement of a particle in sheet 2

γ - shear strain in the glue

σ - normal stress

τ - shear stress in the glue

The lap joint pictured in Figure 3 is taken as being of unit width perpendicular to the paper. It is further considered to be rigidly supported.

Consider the static equilibrium of an element of sheet 1 next to the glue line.

$$\Sigma F_x = 0$$

$$= -p_1 + p_1 + \left(\frac{dp_1}{dx}\right)dx - \tau\, dx$$

This gives:

$$\frac{dp_1}{dx} = \tau \qquad (1)$$

$$\frac{d^2p_1}{dx^2} = \frac{d\tau}{dx} \qquad (2)$$

By definition:

$$\gamma = \frac{\tau}{G}$$

$$= \frac{u_1 - u_2}{t_g}$$

These two equations combine to give:

$$\tau = \frac{G}{t_g}(u_1 - u_2)$$

$$\frac{d\tau}{dx} = \frac{G}{t_g}\left(\frac{du_1}{dx} - \frac{du_2}{dx}\right) \tag{3}$$

Using Hooke's law with (3):

$$\frac{d\tau}{dx} = \frac{G}{Et_g}(\sigma_1 - \sigma_2)$$

$$= \frac{G}{Et_g}\left(\frac{p_1}{t_1} - \frac{p_2}{t_2}\right)$$

$$= \frac{G}{Et_g}\left[\frac{p_1}{t_1} - \frac{N - p_1}{t_2}\right]$$

$$= \frac{G}{Et_g}\left[p_1\left(\frac{1}{t_1} + \frac{1}{t_2}\right) - \frac{N}{t_2}\right]$$

$$= \frac{G}{Et_g}\left(\frac{1}{t_1} + \frac{1}{t_2}\right)\left[p_1 - \frac{N}{t_2\left(\frac{1}{t_1} + \frac{1}{t_2}\right)}\right]$$

$$= \frac{G}{Et_g}\left(\frac{1}{t_1} + \frac{1}{t_2}\right)\left[p_1 - N\left(\frac{t_1}{t_1 + t_2}\right)\right] \tag{4}$$

Next define the constant c^2:

$$c^2 = \frac{G}{Et_g}\left(\frac{1}{t_1} + \frac{1}{t_2}\right) \tag{5}$$

Substituting (5) into (4) and equating the result with (2) gives:

$$\frac{d^2 p_1}{dx^2} = c^2 p_1 - c^2\left(\frac{Nt_1}{t_1+t_2}\right)$$

$$\frac{d^2 p_1}{dx^2} - c^2 p_1 + c^2\left(\frac{Nt_1}{t_1+t_2}\right) = 0 \tag{6}$$

The solution for (6) may be written as:

$$p_1 = N\left(\frac{t_1}{t_1+t_2}\right) + A\sinh cx + B\cosh cx \tag{7}$$

The boundary conditions are:

$$p_1\Big]_{x=0} = N\frac{t_1}{t_1+t_2}$$

$$p_1\Big]_{x=L} = 0$$

From the boundary conditions, it is seen that

$$B = 0$$

$$A = -\frac{Nt_1}{(t_1+t_2)\sinh cL}$$

So that (7) finally becomes:

$$p_1 = \frac{Nt_1}{t_1 + t_2} \left(1 - \frac{\sinh cx}{\sinh cL}\right) \tag{8}$$

Before proceeding further, reference should be made to Figure 3. Formula (8) was developed for either of the two lap joints represented in Figure 3(a). The actual case under consideration is not Figure 3(a), but is Figure 3(b) (this statement is not strictly true, and it is discussed in detail in the next section), and in order for (8) to apply to this latter figure, the dimensions of the test specimen must be made to fit its nomenclature. This will be recognized in the next section.

As stated in the introduction, the main interest is in τ , and not in p_1. The quantity p_1 is merely a tool to assist in the investigation of τ. From (1) and (8):

$$\tau = -\left(\frac{cNt_1}{t_1 + t_2}\right) \frac{\cosh cx}{\sinh cL} \tag{9}$$

From which:

$$\tau_{max} = -\left(\frac{cNt_1}{t_1 + t_2}\right) \frac{\cosh cL}{\sinh cL}$$

$$= -\left(\frac{cNt_1}{t_1 + t_2}\right) \coth cL \tag{10}$$

From (10) it is apparent that as $L \longrightarrow 0$, $\tau_{max} \longrightarrow \infty$. This is what might be expected from the realization that as $L \longrightarrow 0$, there is a diminishing area to resist the applied loads.

Equation (10) is as far as the theoretical analysis need be carried for this work. A discussion of the use to which the theory was put, appears in the next section.

PURPOSE OF TESTS

It was felt that the validity of the theoretical analysis might best be demonstrated by tests that would give answers to two questions:

(a) Does equation (9) give a true representation of the shear stress in the glue?

(b) Is it correct to assume that in a pin-loaded joint, the loading is uniform along the bolt line? That is, can the actual loading, as shown in Figure 2, be accurately represented by a theoretical analysis of the joint of Figure 3?

In order to study the first question, evaluate p_1 for the actual test panels. If p_1 follows the distribution as given by (8), it may safely be assumed that will follow the distribution given by (9). Numerical values that are needed are:

$G - 11 \times 10^4$ pounds per square inch

$E - 10.3 \times 10^6$ pounds per square inch

$t_g - 0.005$ inches

$t_1 - 0.032$ inches

$t_2 - 0.032$ inches

These values substituted into (5) yield:

$$c = 11.55 \ \frac{1}{\text{inches}} \tag{11}$$

Using (11) and the above numerical values in (2):

$$p_1 = N\left(\frac{1}{4} - \frac{\sinh 11.55x}{\sinh 11.55L}\right) \tag{12}$$

$$= N\left(\frac{1}{4} - \frac{e^{11.55x} - e^{-11.55x}}{e^{11.55L} - e^{-11.55L}}\right) \tag{13}$$

A negligible error will be introduced if (13) is rewritten as:

$$p_1 = N\left(0.25 - \frac{e^{11.55x}}{e^{+11.55L}}\right)$$

Then for a change $\frac{\Delta p_1}{p_1} \geqq 0.10$, it will be required that:

$$\frac{e^{11.55x}}{e^{11.55L}} \geqq 0.025$$

But since $\frac{1}{e^{\theta}} \geqq 0.025$ only for $\theta \leqq 3.69$, this requirement may be stated as

$$11.55\,(L - x) \leqq 3.69$$

$$x \geqq L - 0.32 \ \text{inches}$$

This indicates that in order to obtain a 10% reduction in p_1 it would be necessary to take measurements of strain at a distance of 0.32 inches from the edge of the doubler. For a greater reduction in p_1, observations would have been necessary even nearer the edge. Because of the lack of experience in experimental techniques, particularly those involving the proper handling and mounting of electric resistance strain gages, it was not felt that much of value could be obtained from an investigation along these lines. Furthermore, it was believed that any study of this question should be based on the correctness of the assumption (b) above. For unless this assumption were correct, there would be little point in trying to evaluate the accuracy of (8).

For these reasons, all tests were carried out for the purpose of answering (b) above.

EQUIPMENT

All test specimens were made of 75S-T6 Alclad aluminum alloy. A sample is illustrated in Figure 4 and pictured in Figure 5. They were made by the student from the two 16 x 36 inch glued but undrilled panels furnished by the Chance Vought Division of The United Aircraft Corporation, Dallas, Texas. Doublers were glued at the factory in order to duplicate actual manufacturing conditions.

The nominal thickness of the core was given as 0.064 inches, and the nominal thickness of the doublers was given as 0.032 inches. Measurements at many spots along the edges of each cut test specimen indicated that it varied from 0.065 inches to 0.068 inches for the core, and from 0.032 inches to 0.035 inches for the doublers.

Nominal glue thickness was given as 0.006 to 0.009 inches. A laboratory check in two spots indicated that glue thickness was 0.005 inches. This check was made using the microscope from a Beggs Deformeter set. The instrument was rather crudely calibrated with a Brown and Sharp machinists' scale which was divided into 0.01 inch spaces.

Lap length, L, as defined in the theoretical development, was assumed to be the distance between the center line

of the loading pin, and the edge of the doubler that was nearest the end of the panel under uniform tension. Five lap lengths were tested: 1.5,2, 2.5, 3, and 6 inches.

SR-4 electric resistance strain gages were glued on at the University as shown in Figures 4 and 5. For each strain gage shown in Figure 5, there is another strain gage exactly opposite, on the other side of the specimen. The type A-11 strain gage (one inch gage length) was used wherever possible, and the type A-8 gage (one-eighth inch gage length) was used as space limitations dictated. A total of ten gages was used on each side of each plate.

All strain gages were wired into a Twenty Point Switching Unit, and then to a Type L Portable Strain Indicator, which gave direct indications of strain, in units of micro-inches per inch.

Tests were conducted on the 120,000 pound Universal Testing Machine located in the University of Minnesota Experimental Engineering Building. Two views of the specimen in the testing machine are presented as Figures 6 and 7. It can be seen from these pictures (Figure 7 in particular), that the gripping jaws normally used with the Universal Testing Machine were not used for the tests. Because it was understood

that such grips have a tendency to slip, the tee-sections pictured were used to hold the specimen in the machine and transmit the load. All bolts shown were tightened with wrenches while a load of about 1000 pounds was held, in order to insure proper alignment of the tees with the faces that they matched on the machine. Separators kept the lower pulling strap from pressing against the strain gages under it.

The SR-4 strain gages, the Twenty point Switching Unit, the Type L Portable Strain Indicator, and the Universal Testing Machine were all manufactured by the Baldwin-Lima-Hamilton Corporation, Eddystone Division, Southwark Shop, Philadelphia, 42, Pennsylvania.

PROCEDURE

The laboratory testing procedure consisted of applying loads at 1000 pound intervals, and recording the strains indicated by each gage. As can be seen by Table I, the laboratory data sheet, a load of 100 pounds was considered to be the "zero" load. Increments of 1000 pounds required that the testing machine be loaded to 1100, 2100, 3100 pounds, and so on, up to a maximum of 8100 pounds. This maximum was dictated by the bearing strength at the hole around the loading pin.

Front and back strain gages were read and averaged in order to give the net strain at each point on the specimen.

The only variation from this routine procedure was required when strain gage seven of the six inch lap length plate indicated that part of the plate was in compression instead of the usual tension. The strains were checked by placing Huggenberger Tensometers on each side of the panel, in line with gages 7-10, but 11½ inches from gages 7-f and 7-b.

Considerable time and effort was spent trying to obtain uniform loading conditions as measured by strain gages 1-3. The results of these efforts did not produce uniform

loading, but they did make the load as uniform as it was felt was possible with the mounting arrangement in use.

RESULTS AND DISCUSSION

Actual strain indicator readings are given in Tables I(a)-(e). The strains on the front and back of each panel, and their averages, are presented in Tables II(a)-(e). Figures 8-10 are graphical interpretations of the results.

As shown by Figures 8(a)-(e), the strains are not uniform along the bolt line, L, but they increase up to the edge of the hole. The peak loads decrease as the lap length increases from 1.5 to 3 inches, but they increase sharply for a lap length of 6 inches. The latter plate exhibited further unusual characteristics, in that it was in compression along its edges, as shown by Figure 8(e).

There was some doubt as to the accuracy of the electric strain gages at the point of compression, so, in order to check the readings, mechanical strain gages were placed symmetrically opposite them, as explained in the section giving procedures. The mechanical strain gages also indicated compression. There is no way to account for this effect by application of the theory under investigation. The compressive effect was still being felt at the $\frac{1}{2}$L line. This is indicated by the fact that the strains at the outer edge of the panel, as given by Figure 9(e), are smaller than those shown

in any of the other curves of Figure 9.

The strain patterns of Figures 9(a)-(e) are similar, with the exception of the curves for the two inch lap length. They were considerably less at any point on this plate than they were on any other plate. This is not explained by equation (8).

The shape of the strain curves along the $\frac{1}{2}$L line was assumed to be similar to the shape of the curves showing strain along the bolt line. This, or some other assumption as to shape was necessary due to the limited number of strain gages along this line. As might be expected from Saint-Venant's principle, the strain curves tend to flatten out as the lap length increases, and the $\frac{1}{2}$L line is farther removed from the edge of the hole.

The most interesting results are found in an inspection of Figures 10(a)-(e). For convenience make the following definitions:

p_{1u} - the p_1 that would obtain in lap joints such as those of Figure 3, where loading is uniform

$\epsilon_{1u}, \sigma_{1u}$ - strains and stresses due to p_{1u}

p_{1act} - the actual p_1 determined by testing the joint of Figure 2

ϵ_{1act} - strains resulting from p_{1act}

σ_{1act} - stresses resulting from p_{1act}

Using the above, define next:

$$K = \frac{p_{1act}}{p_{1u}} = \frac{\epsilon_{1act}}{\epsilon_{1u}} = \frac{\sigma_{1act}}{\sigma_{1u}}$$

Figures 10(a)-(e), then, are plots showing how K varies with lateral position along the line L, and along the line $\frac{1}{2}$L. A net load of 8000 pounds was used for each figure. This load was picked arbitrarily, and similar curves would have been found for other loads, because of the similarity of the relationship between the strain curves at any load.

Area ABCD is the area that would result from a uniform loading of the lap joint of Figure 3. It is 6.0 square inches for all of the graphs. This is, of course, an exact measurement. The other areas that have been noted on the figures are all approximate, because the curves were faired in using limited laboratory data.

For the 1.5 inch lap length plate, the area under the curve indicating loading along the line L is only 5.0 square inches. This would seem to indicate that even at the

line L, more load is being carried by the middle plate than is being carried by the two outer plates along which strains were measured. Along the line $\frac{1}{2}$L, the area under the curve is 4.6 inches. This shows that some of the load that was initially in the outer sheets has been transferred into the middle sheet. According to equation (8), the amount of load so transferred at the $\frac{1}{2}$L line would be imperceptible, but Figure 10(a) indicates that such is not the case.

The same conditions pertain for the plate with a 2 inch lap length, except that even less of the total load is acting at the bolt line (i.e., the line L).

The plate with a 3 inch lap length shows results similar to the plate with a 1.5 inch lap length. But the 2.5 and 6 inch lap length plates exhibit a peculiar phenomenon. In each of these panels there appears to be a greater load on the outer plates along the $\frac{1}{2}$L line than there is along the line L. The effect is most pronounced for the 6 inch lap length plate. This appears to indicate that some of the load that the pin applied to the center sheet was transmitted back to the outside sheet. This may explain the compressive forces acting at the edge of the 6 inch lap length plate, but if it does, it raises the question as to why the same transfer phenomenon does not produce compression in the

plate with a 2.5 inch lap length.

In all probability, the only safe conclusion that can be drawn from the data is that hole and pin combinations that are apparently the same, may produce variable and inconsistent results. As can be seen from Figure 7, a one inch bolt was used to apply the load at the hole. The nut was tightened with what felt like the same torque each time, but a torque wrench was not used. The holes were drilled with considerable care, but even so, it was necessary to file a portion of the edges of each hole in order to permit passage of the bolt.

If such a variation can occur while using laboratory techniques, it is even more likely that factory production methods will produce erratic results. It is believed that further investigation might well be directed at making more accurate determinations of the bearing pattern produced by a bolt or a rivet. This is not a conclusion along the lines of those that were sought when the work was initiated, but it may be that it is important, and worthy of further investigation.

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions may be summarized from the preceding section:

(a) Equation (8) does not hold.

(b) It is incorrect to assume that in a pin-loaded joint, the loading is uniform along the bolt-line.

(c) The compression of the 6 inch lap length plate can not be accounted for by the theory under investigation.

(d) The transfer of some of the load from the inner sheets to the outer sheets can not be accounted for by the present theory.

(e) Hole and pin combinations that are apparently the same, may produce strain patterns that vary widely and inconsistently.

(f) Bolt or pin bearing may not be uniform along the entire bearing surface.

It is recommended that further study be made of the pattern of bolt or pin bearing.

TABLE I (a)

LABORATORY DATA FOR TEST SPECIMEN HAVING A 1.5 INCH LAP LENGTH.

(Numbers given are actual dial readings from strain indicator. f or b following gage number indicates if gage on front or back of plate.)

	Load pounds								
Gage	100	1,100	2,100	3,100	4,100	5,100	6,100	7,100	8,100
1-f	10,250	10,333	10,455	10,575	10,700	10,820	10,940	11,060	11,160
1-b	11,410	11,540	11,635	11,733	11,843	11,960	12,070	12,190	12,290
2-f	10,890	10,980	11,110	11,228	11,340	11,450	11,560	11,658	11,735
2-b	11,410	11,548	11,648	11,745	11,845	11,940	12,045	12,135	12,205
3-f	This gage did not function.								
3-b	11,345	11,450	11,528	11,613	11,710	11,818	11,920	12,030	12,120
4-f	10,528	10,620	10,650	10,670	10,688	10,700	10,720	10,750	10,770
4-b	11,030	10,990	10,990	11,010	11,038	11,075	11,115	11,155	11,190
5-f	10,000	10,225	10,390	10,525	10,660	10,780	10,910	11,040	11,135
5-b	12,255	12,090	12,352	12,425	12,492	12,570	12,640	12,705	12,760
6-f	10,868	10,900	10,930	10,952	10,980	11,000	11,025	11,050	11,070
6-b	10,980	11,000	11,020	11,050	11,072	11,100	11,130	11,150	11,180
7-f	10,010	10,108	10,148	10,170	10,193	10,218	10,240	10,265	10,290
7-b	6,615	6,572	6,572	6,590	6,620	6,655	6,690	6,730	6,760
8-f	10,700	10,810	10,875	10,921	10,965	11,005	11,048	11,083	11,110
8-b	11,385	11,343	11,350	11,370	11,403	11,445	11,480	11,520	11,553
9-f	9,750	9,875	9,988	10,088	10,190	10,300	10,398	10,500	10,580
9-b	10,830	10,925	11,032	11,140	11,243	11,350	11,460	11,572	11,653
10-f	11,450	11,770	12,053	12,315	12,600	12,878	13,150	13,428	13,650
10-b	10,135	10,392	10,650	10,875	11,100	11,330	11,560	11,770	11,935

TABLE I (b)

LABORATORY DATA FOR TEST SPECIMEN HAVING A 2.0 INCH LAP LENGTH.

(Numbers given are actual dial readings from strain indicator. f or b following gage number indicates if gage on front or back of plate.)

	Load - pounds								
Gage	100	1,100	2,100	3,100	4,100	5,100	6,100	7,100	8,100
1-f	11,200	11,325	11,445	11,565	11,685	11,825	11,950	12,090	12,240
1-b	10,925	11,040	11,142	11,250	11,360	11,470	11,590	11,730	11,860
2-f	11,780	11,910	12,042	12,170	12,280	12,390	12,500	12,590	12,685
2-b	11,205	11,343	11,460	11,580	11,680	11,775	11,880	11,975	12,060
3-f	11,630	11,715	11,895	12,020	12,140	12,262	12,390	10,520	12,665
3-b	11,663	11,765	11,870	11,980	12,100	12,210	12,332	12,470	12,605
4-f	10,840	10,920	10,950	10,985	10,970	10,990	11,000	11,022	11,040
4-b	10,580	10,520	10,515	10,525	10,562	10,612	10,652	10,700	10,750
5-f	10,490	10,660	10,808	10,930	10,980	11,062	11,120	11,180	11,225
5-b	12,445	12,390	12,360	12,350	12,403	12,470	12,510	12,630	12,720
6-f	10,585	10,745	10,880	11,020	11,085	11,150	11,215	11,275	11,330
6-b	10,782	10,730	10,695	10,650	10,670	10,700	10,730	10,765	10,803
7-f	11,210	11,295	11,333	11,360	11,375	11,390	11,415	11,440	11,460
7-b	10,340	10,280	10,265	10,270	10,305	10,340	10,375	10,420	10,465
8-f	8,380	8,480	8,540	8,595	8,623	8,652	8,685	8,720	8,750
8-b	10,820	10,785	10,790	10,808	10,845	10,885	10,930	10,975	11,028
9-f	11,220	11,340	11,442	11,540	11,630	11,720	11,812	11,920	12,010
9-b	10,105	10,240	10,385	10,525	10,640	10,750	10,868	10,980	11,110
10-f	11,375	11,603	11,800	12,000	12,170	12,360	12,550	12,735	12,940
10-b	11,470	11,750	12,010	12,265	12,510	12,758	13,000	13,232	13,468

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[illegible]

[illegible]

[illegible]

[illegible]

TABLE I (c)

LABORATORY DATA FOR TEST SPECIMEN HAVING A 2.5 INCH LAP LENGTH.

(Numbers given are actual dial readings from strain indicator. f or b following gage number indicates if gage on front or back of plate.)

	Load - pounds								
Gage	100	1,100	2,100	3,100	4,100	5,100	6,100	7,100	8,100
1-f	11,500	11,620	11,722	11,830	11,930	12,040	12,145	12,250	12,385
1-b	11,158	11,250	11,370	11,490	11,605	11,720	11,840	11,958	12,068
2-f	10,850	10,985	11,100	11,220	11,335	11,452	11,570	11,680	11,790
2-b	11,050	11,142	11,258	11,372	11,490	11,610	11,730	11,845	11,952
3-f	11,132	12,272	11,395	11,515	11,630	11,750	11,870	11,985	12,100
3-b	10,990	11,068	11,168	11,275	11,385	11,495	11,610	11,725	11,840
4-f	10,500	10,522	10,550	10,580	10,612	10,650	10,682	10,720	10,750
4-b	10,630	10,660	10,690	10,720	10,750	10,775	10,803	10,830	10,858
5-f	11,635	11,712	11,782	11,870	11,955	12,045	12,140	12,233	12,330
5-b	12,060	12,205	12,352	12,508	12,650	12,780	12,912	13,030	13,140
6-f	10,600	10,622	10,650	10,680	10,720	10,762	10,815	10,872	10,930
6-b	11,642	11,740	11,830	11,925	12,015	12,095	12,778	12,250	12,315
7-f	11,578	11,590	11,610	11,630	11,655	11,680	11,710	11,740	11,765
7-b	11,660	11,685	11,712	11,740	11,763	11,790	11,810	11,835	11,858
8-f	11,480	11,505	11,540	11,570	11,609	11,645	11,685	11,725	11,763
8-b	12,240	12,285	12,325	12,368	12,405	12,430	12,480	12,512	12,550
9-f	11,182	11,290	11,400	11,508	11,620	11,730	11,845	11,960	12,065
9-b	12,223	12,312	12,405	12,500	12,588	12,680	12,770	12,860	12,950
10-f	10,900	11,145	11,400	11,640	11,890	12,140	12,380	12,630	12,852
10-b	11,800	12,000	12,205	12,408	12,600	12,805	12,990	13,185	13,345

TABLE I (d)

LABORATORY DATA FOR TEST SPECIMEN HAVING A 3.0 INCH LAP LENGTH.

(Numbers given are actual dial readings from strain indicator. f or b following gage number indicates if gage on front or back of plate.)

	Load - pounds								
Gage	100	1,100	2,100	3,100	4,100	5,100	6,100	7,100	8,100
1-f	10,642	10,708	10,820	10,920	11,025	11,130	11,240	11,342	11,452
1-b	10,915	11,040	11,050	11,250	11,378	11,470	11,585	11,688	11,802
2-f	11,902	11,995	12,115	12,230	12,340	12,452	12,570	12,680	12,800
2-b	11,820	11,970	12,090	12,208	12,338	12,460	12,593	12,710	12,848
3-f	10,500	10,580	10,715	10,840	10,960	11,080	11,200	11,315	11,438
3-b	11,528	11,658	11,752	11,840	11,940	12,042	12,148	12,250	12,362
4-f	11,482	11,520	11,557	11,590	11,620	11,650	11,680	11,710	11,749
4-b	11,752	11,769	11,805	11,825	11,853	11,885	11,915	11,945	11,978
5-f	10,888	11,015	11,125	11,248	11,350	11,450	11,550	11,650	11,752
5-b	11,390	11,462	11,575	11,660	11,760	11,870	11,982	12,080	12,188
6-f	10,285	10,385	10,463	10,558	10,638	10,708	10,782	10,855	10,940
6-b	10,050	10,080	10,160	10,212	10,275	10,352	10,433	10,502	10,580
7-f	11,040	11,068	11,095	11,118	11,138	11,155	11,175	11,198	11,222
7-b	10,730	10,738	10,762	10,775	10,795	10,820	10,843	10,862	10,890
8-f	10,460	10,510	10,550	10,595	10,638	10,675	10,718	10,755	10,800
8-b	10,775	10,800	10,848	10,873	10,908	10,950	10,990	11,022	11,063
9-f	10,860	10,975	11,088	11,200	11,320	11,440	11,562	11,682	11,815
9-b	10,580	10,685	10,800	10,905	11,015	11,122	11,235	11,342	11,458
10-f	10,935	11,140	11,353	11,580	11,800	12,020	12,240	12,450	12,650
10-b	13,010	13,325	13,540	13,765	13,962	14,182	14,395	14,603	14,790

TABLE I (e)

LABORATORY DATA FOR TEST SPECIMEN HAVING A 6.0 INCH LAP LENGTH.

(Numbers given are actual dial readings from strain indicator. f or b following gage number indicates if gage on front or back of plate.)

	Load - pounds								
Gage	100	1,100	2,100	3,100	4,100	5,100	6,100	7,100	8,100
1-f	10,785	10,908	10,990	11,075	11,170	11,270	11,380	11,502	11,615
1-b	11,012	11,100	11,230	11,360	11,500	11,630	11,755	11,880	12,012
2-f	10,625	10,775	10,884	10,990	11,095	11,200	11,310	11,428	11,532
2-b	10,370	10,490	10,625	10,760	10,890	11,015	11,138	11,248	11,372
3-f	11,065	11,288	11,370	11,450	11,540	11,635	11,740	11,850	11,950
3-b	11,070	11,170	11,315	11,463	11,600	11,732	11,860	11,990	12,110
4-f	10,433	10,460	10,482	10,502	10,528	10,550	10,570	10,585	10,600
4-b	11,640	11,653	11,660	11,670	11,680	11,690	11,710	11,730	11,745
5-f	11,315	11,420	11,528	11,628	11,735	11,840	11,940	12,040	12,130
5-b	10,770	10,863	10,953	11,040	11,123	11,215	11,315	11,422	11,520
6-f	10,910	11,003	11,100	11,200	11,303	11,405	11,500	11,592	11,682
6-b	11,730	11,829	11,920	13,010	12,098	12,192	12,290	12,400	12,500
7-f	10,312	10,310	10,305	10,300	10,300	10,295	10,290	10,285	10,280
7-b	10,845	10,275	10,285	10,300	10,312	10,330	10,350	10,372	10,390
8-f	11,289	11,303	11,325	11,345	11,365	11,288	11,410	11,430	11,450
8-b	10,260	10,275	10,285	10,300	10,312	10,330	10,350	10,372	10,390
9-f	9,310	9,475	9,638	8,800	9,952	10,115	10,275	10,440	10,620
9-b	11,328	11,490	11,640	11,792	11,948	12,120	12,265	12,430	12,588
10-f	10,990	11,345	11,690	12,040	12,365	12,710	13,055	13,410	13,780
10-b	10,715	11,050	11,350	11,648	11,940	12,242	12,540	12,830	13,120

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[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
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[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

TABLE II (a)

VARIATION OF STRAIN WITH APPLIED LOAD, FOR SPECIMEN HAVING A 1.5 INCH LAP LENGTH.

(f or b following gage number indicates if gage on front or back of plate. Ave. indicates average of front and back.)

Load - pounds

Gage	100	1,100	2,100	3,100	4,100	5,100	6,100	7,100	8,100
1-f	0	83	205	325	450	570	690	810	910
1-b	0	130	225	323	443	550	660	780	880
Ave.	0	107	215	324	446	560	675	795	895
2-f	0	90	220	338	450	560	670	768	845
2-b	0	138	238	335	435	530	635	725	795
Ave.	0	114	229	336	442	545	652	746	820
3-f	This gage did not function.								
3-b	0	105	183	268	365	473	575	685	775
Ave.*	0	82	173	267	370	485	591	603	795
4-f	0	92	122	142	160	172	192	222	242
4-b	0	-40	-40	-20	8	45	85	125	160
Ave.	0	26	41	61	84	108	138	174	201
5-f	0	225	390	525	660	780	910	1040	1135
5-b	0	-165	97	170	237	315	385	450	505
Ave.	0	30	243	347	448	547	647	745	820
6-f	0	32	62	84	112	132	157	182	202
6-b	0	20	40	70	92	120	150	170	200
Ave.	0	26	51	77	102	126	153	176	201
7-f	0	98	138	160	183	208	230	255	280
7-b	0	-43	-43	-25	5	40	75	115	145
Ave.	0	27	47	67	94	124	152	185	212
8-f	0	110	175	221	265	305	348	383	410
8-b	0	-42	-35	-15	18	60	95	135	168
Ave.	0	34	70	103	141	182	221	259	289
9-f	0	125	238	338	440	550	648	750	830
9-b	0	105	212	310	413	520	630	742	823
Ave.	0	115	225	324	426	535	639	746	826
10-f	0	288	603	865	1150	1438	1700	1978	2200
10-b	0	257	515	740	965	1195	1435	1635	1800
Ave.	0	288	559	802	1058	1326	1658	1806	2000

*This average computed by assuming that, had 3-f functioned, it would have differed from 3-b by same amount as 1-f and 1-b, or 2-f and 2-b differed.

TABLE II (b)

VARIATION OF STRAIN WITH APPLIED LOAD FOR SPECIMEN HAVING A 2.0 INCH LAP LENGTH.

(f or b following gage number indicates if gage on front or back of plate. Ave. indicates average of front and back.)

	Load - pounds								
Gage	100	1,100	2,100	3,100	4,100	5,100	6,100	7,100	8,100
1-f	0	125	245	365	485	625	750	890	1040
1-b	0	105	217	325	435	545	665	805	935
Ave.	0	115	231	345	460	595	707	847	982
2-f	0	130	262	390	500	610	720	810	905
2-b	0	138	255	375	475	590	695	770	855
Ave.	0	134	258	382	487	600	707	790	880
3-f	0	85	265	370	490	632	760	890	1030
3-b	0	102	207	317	437	547	669	807	942
Ave.	0	93	236	344	464	589	714	849	986
4-f	0	80	110	145	130	150	160	182	200
4-b	0	-60	-65	-55	-18	32	72	120	170
Ave.	0	10	17	50	56	91	116	151	185
5-f	0	170	318	440	490	572	630	690	735
5-b	0	-55	-85	-95	-42	25	65	185	275
Ave.	0	57	116	173	224	298	347	437	515
6-f	0	160	295	435	500	565	630	[illegible]	745
6-b	0	-52	-87	-132	-112	-82	-52	-17	21
Ave.	0	54	104	151	194	241	289	336	383
7-f	0	85	123	150	165	180	205	230	250
7-b	0	-60	-75	-70	-35	0	35	80	125
Ave.	0	12	24	40	65	90	120	155	187
8-f	0	100	160	215	240	269	305	340	370
8-b	0	-35	-30	-12	25	65	110	155	208
Ave.	0	32	65	101	132	167	208	247	288
9-f	0	120	222	320	410	500	592	700	790
9-b	0	135	280	420	535	645	763	875	905
Ave.	0	128	251	370	472	573	677	787	847
10-f	0	228	425	625	795	985	1175	1360	1565
10-b	0	280	540	795	1040	1288	1530	1762	1998
Ave.	0	254	482	710	917	1136	1353	1561	1781

TABLE II (c)

VARIATION OF STRAIN WITH APPLIED LOAD FOR SPECIMEN HAVING A 2.5 INCH LAP LENGTH.

(f or b following gage number indicates if gage on front or back of plate. Ave. indicates average of front and back.)

	Load - pounds								
Gage	100	1,100	2,100	3,100	4,100	5,100	6,100	7,100	8,100
1-f	0	120	222	330	430	540	645	750	858
1-b	0	92	212	332	447	562	672	800	910
Ave.	0	106	217	331	438	551	658	775	884
2-f	0	135	250	370	485	602	720	830	940
2-b	0	92	208	322	450	560	680	795	902
Ave.	0	103	229	346	467	581	700	812	921
3-f	0	140	262	383	498	618	738	853	968
3-b	0	78	178	285	395	505	620	735	850
Ave.	0	119	200	334	446	562	679	794	909
4-f	0	22	50	80	112	150	182	220	250
4-b	0	30	60	90	120	145	173	200	228
Ave.	0	26	55	85	116	147	186	210	239
5-f	0	72	147	235	320	410	505	598	695
5-b	0	145	292	458	590	720	852	970	1080
Ave.	0	108	220	346	455	565	678	784	888
6-f	0	22	20	80	120	162	215	272	330
6-b	0	98	188	283	373	453	536	598	673
Ave.	0	60	108	181	246	307	375	435	501
7-f	0	12	32	52	77	102	132	162	187
7-b	0	25	52	80	103	130	150	175	198
Ave.	0	18	42	66	90	116	141	168	192
8-f	0	25	60	90	129	165	205	245	283
8-b	0	45	85	128	165	190	240	272	310
Ave.	0	35	72	108	147	177	222	259	297
9-f	0	108	218	326	438	548	663	778	883
9-b	0	89	182	277	365	457	547	637	727
Ave.	0	98	200	301	401	502	595	707	805
10-f	0	245	500	740	990	1240	1480	1730	1592
10-b	0	200	405	608	800	1005	1190	1385	1545
Ave.	0	227	452	674	895	1123	1335	1557	1748

TABLE II (d)

VARIATION OF STRAIN WITH APPLIED LOAD FOR SPECIMEN HAVING A 3.0 INCH LAP LENGTH.

(f or b following gage number indicates if gage on front or back of plate. Ave. indicates average of front and back.)

	Load - pounds								
Gage	100	1,100	2,100	3,100	4,100	5,100	6,100	7,100	8,100
1-f	0	66	178	278	383	488	598	700	810
1-b	0	125	135	335	463	555	670	773	887
Ave.	0	96	156	336	423	521	634	736	848
2-f	0	93	213	328	438	550	662	778	898
2-b	0	150	270	388	578	640	773	890	1028
Ave.	0	121	241	358	478	595	717	834	963
3-f	0	80	215	340	460	580	700	815	938
3-b	0	140	224	312	412	514	620	722	834
Ave.	0	110	219	326	436	547	660	775	886
4-f	0	38	75	108	138	168	198	228	267
4-b	0	17	53	73	101	133	163	193	226
Ave.	0	27	64	90	119	150	180	210	241
5-f	0	127	237	360	462	562	662	762	864
5-b	0	72	185	270	370	480	592	690	798
Ave.	0	99	211	315	416	521	627	726	831
6-f	0	100	178	273	353	423	497	570	655
6-b	0	30	110	162	225	302	383	452	530
Ave.	0	65	144	217	289	362	440	511	592
7-f	0	28	55	78	98	115	135	158	182
7-b	0	8	32	45	65	90	113	132	160
Ave.	0	18	43	61	81	102	124	145	171
8-f	0	50	90	135	178	215	258	295	330
8-b	0	25	73	98	133	175	215	247	288
Ave.	0	37	82	116	155	195	236	271	309
9-f	0	115	228	340	460	580	702	822	955
9-b	0	105	220	325	435	542	655	762	878
Ave.	0	110	224	332	447	559	679	792	917
10-f	0	205	418	645	865	1075	1295	1515	1715
10-b	0	315	530	755	952	1172	1385	1593	1780
Ave.	0	260	474	700	908	1124	1340	1554	1747

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[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
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TABLE II (e)

VARIATION OF STRAIN WITH APPLIED LOAD FOR SPECIMEN HAVING A 6.0 INCH LAP LENGTH.

(f or b following gage number indicates if gage on front or back of plate. Ave. indicates average of front and back.)

	Load - pounds								
Gage	100	1,100	2,100	3,100	4,100	5,100	6,100	7,100	8,100
1-f	0	123	205	290	385	485	595	717	830
1-b	0	88	218	348	488	618	743	868	1000
Ave.	0	105	211	319	436	551	669	792	915
2-f	0	150	259	365	470	575	685	803	908
2-b	0	120	255	390	520	645	768	878	1002
Ave.	0	135	257	377	495	617	726	840	955
3-f	0	223	305	385	475	570	675	785	885
3-b	0	100	245	393	530	662	790	920	1040
Ave.	0	161	275	389	502	606	732	852	962
4-f	0	27	49	69	95	117	137	152	167
4-b	0	13	20	30	40	50	70	90	105
Ave.	0	20	35	50	67	83	103	121	136
5-f	0	105	213	313	420	525	625	725	815
5-b	0	93	183	270	353	445	545	652	750
Ave.	0	99	198	291	386	495	595	688	783
6-f	0	93	190	290	393	495	590	682	772
6-b	0	99	190	280	365	462	560	670	770
Ave.	0	96	190	285	379	478	575	676	771
7-f*	0	-2	-7	-12	-12	-17	-22	-27	-32
7-b*	0	-5	-15	-25	-35	-43	-45	-45	-55
Ave.	0	-3	-11	-18	-24	-30	-34	-36	-44
8-f	0	14	36	56	76	99	121	141	161
8-b	0	15	25	40	52	70	90	112	130
Ave.	0	14	30	44	64	85	105	127	145
9-f	0	165	328	490	642	805	965	1130	1310
9-b	0	162	312	464	620	792	937	1102	1260
Ave.	0	163	320	[illegible]	631	798	951	1116	1285
10-f	0	355	700	1050	1375	1720	2065	2420	2790
10-b	0	335	635	932	1225	1527	1825	2115	2405
Ave.	0	345	667	966	1300	1623	1945	2267	2598

*Readings for 7-f and 7-b were checked with two Huggenberger Tensometers in a line with gages 7-10, but $11\frac{1}{2}$ inches from gages 7-f and 7-b.

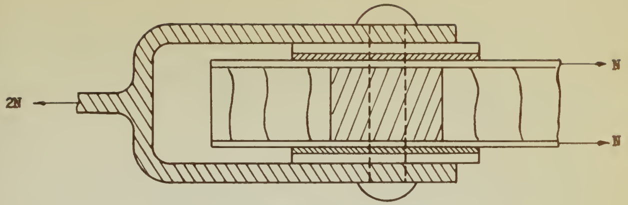


Figure 1 - One type of sandwich fitting.

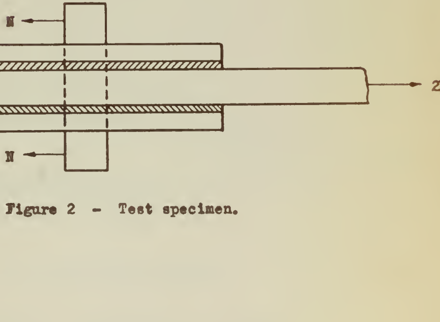
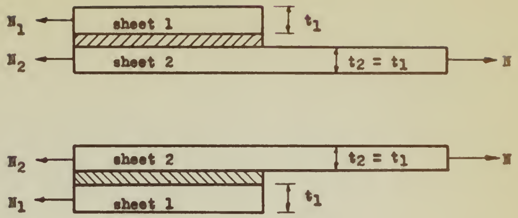
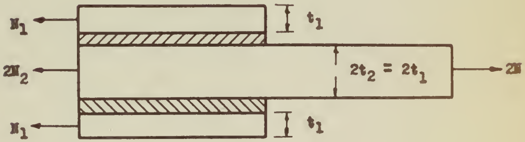


Figure 2 - Test specimen.

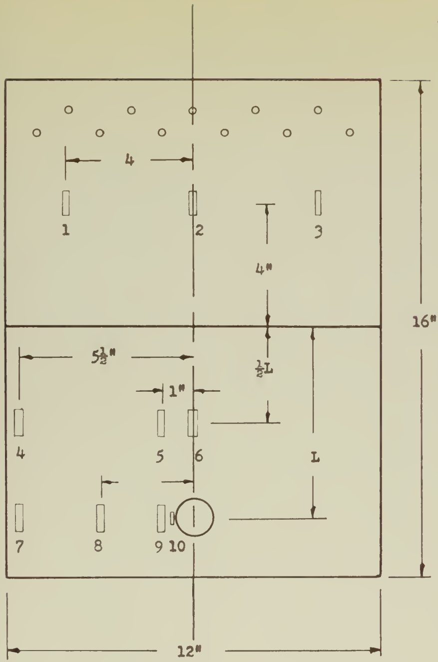


(a) Case for which theory was developed.

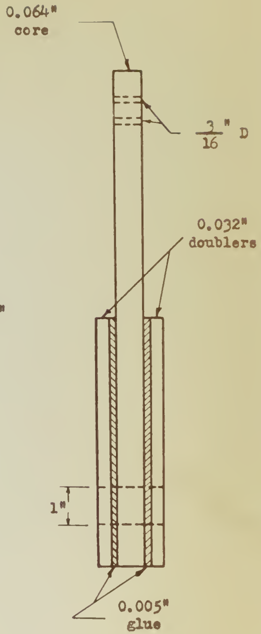


(b) Actual test specimen

Figure 3 - Two types of lap joint.



(a) Front view, showing location and numbering of strain gages.



(b) Side view.

Figure 4 - Test specimen.

Figure 5 - Test specimen of three inch lap length. Shown are nine A-11 strain gages and one A-8.

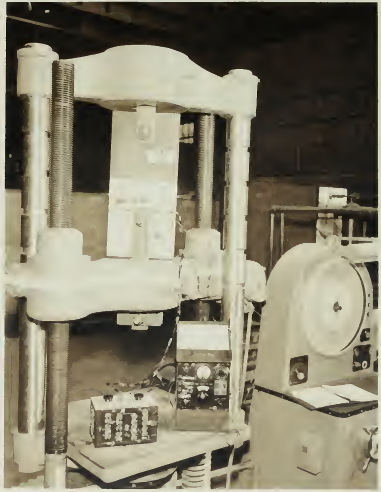


Figure 6 - Specimen mounted in testing machine, showing load indicator dial, switch box, and strain indicator.

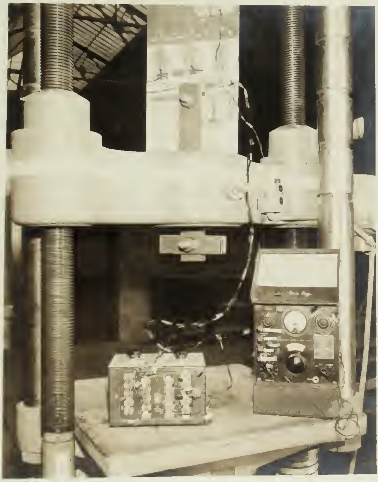


Figure 7 - Specimen mounted in testing machine. Close-up, showing tee-section used in place of standard grips.

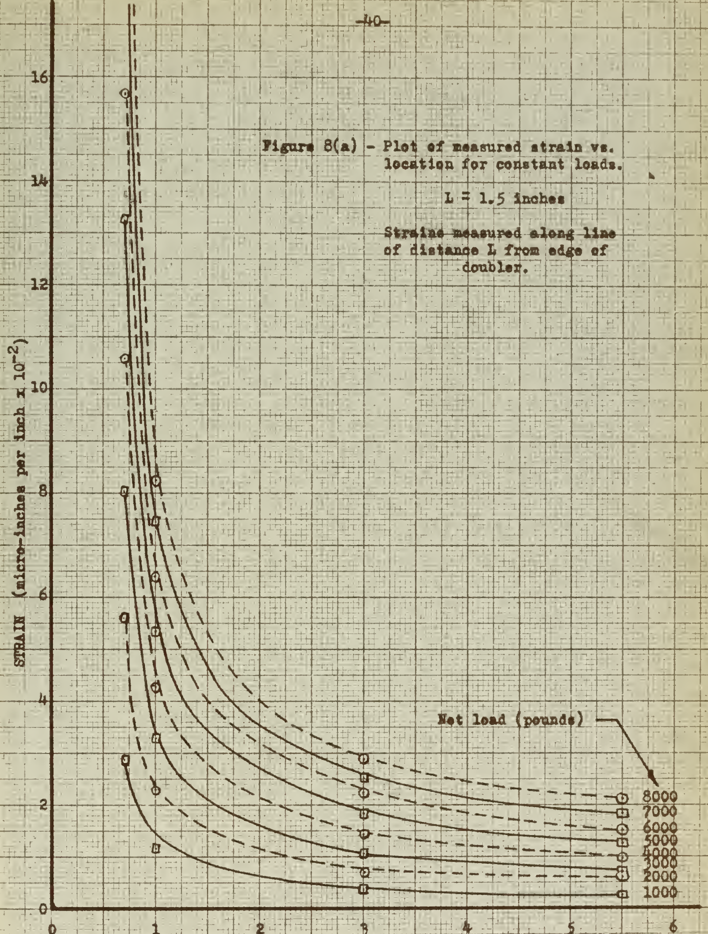


Figure 8(a) - Plot of measured strain vs. location for constant loads.
L = 1.5 inches
Strains measured along line of distance L from edge of doubler.
STRAIN (micro-inches per inch x 10^{-2})
DISTANCE FROM HOLE CENTERLINE (inches)
Net load (pounds)
8000
7000
6000
5000
4000
3000
2000
1000
0
2
4
6
8
10
12
14
16
0
1
2
3
4
5
6

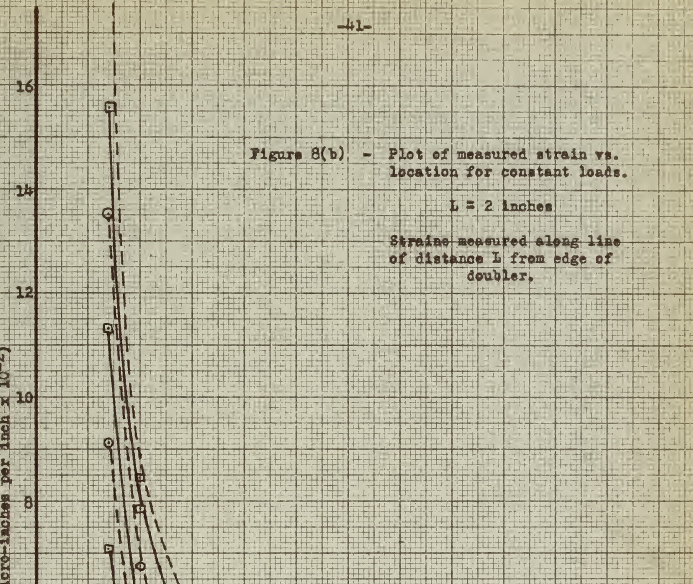


Figure 8(b) - Plot of measured strain vs. location for constant loads.
L = 2 inches
Strains measured along line of distance L from edge of doubler.
Net load (pounds)
8000
7000
6000
5000
4000
3000
2000
1000
STRAIN (micro-inches per inch x 10^{-2})
DISTANCE FROM HOLE CENTERLINE (inches)
0
1
2
3
4
5
6
2
4
6
8
10
12
14
16

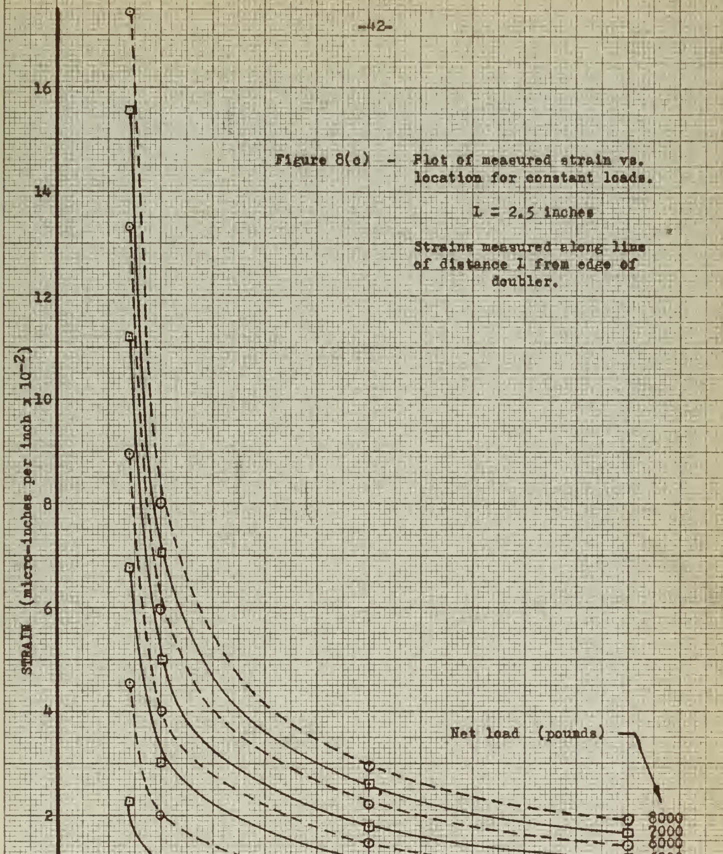


Figure 8(c) - Plot of measured strain vs. location for constant loads.
L = 2.5 inches
Strains measured along line of distance L from edge of doubler.
Net load (pounds)
8000
7000
6000
5000
4000
3000
2000
1000
STRAIN (micro-inches per inch x 10^{-2})
DISTANCE FROM HOLE CENTERLINE (inches)
0
2
4
6
8
10
12
14
16
1
3
5

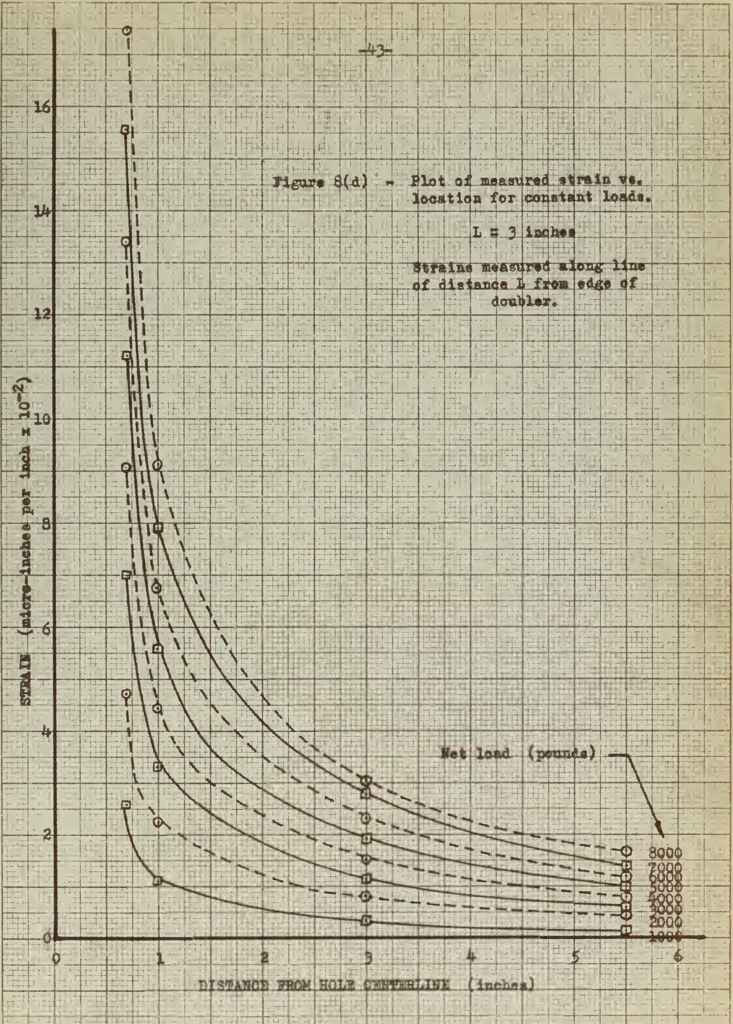


Figure 8(d) - Plot of measured strain vs. location for constant loads.
L = 3 inches
Strains measured along line of distance L from edge of doubler.
Net load (pounds)
8000
7000
6000
5000
4000
3000
2000
1000
STRAIN (micro-inches per inch x 10^-2)
0
2
4
6
8
10
12
14
16
0
1
2
3
4
5
6
DISTANCE FROM HOLE CENTERLINE (inches)

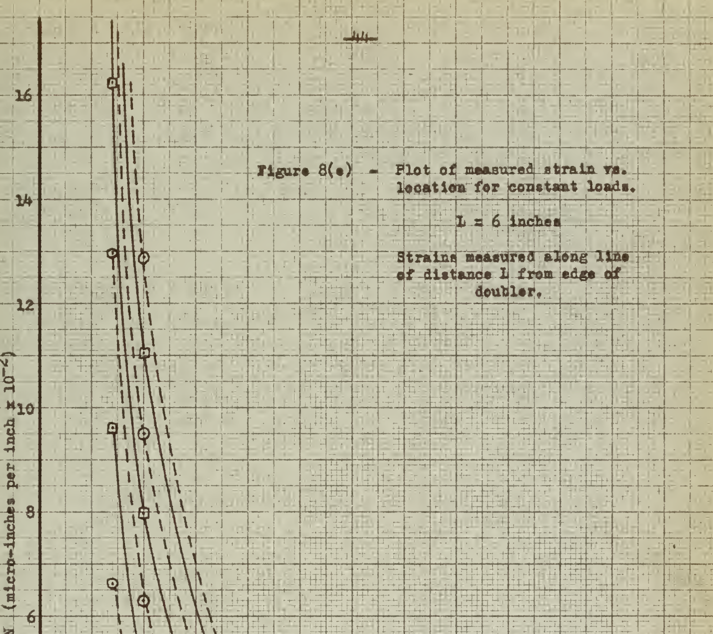


Figure 8(e) - Plot of measured strain vs. location for constant loads.
L = 6 inches
Strains measured along line of distance L from edge of doubler.
Net load (pounds)
1000
8000
STRAIN (micro-inches per inch x 10^{-2})
DISTANCE FROM HOLE CENTERLINE (inches)
0
2
4
6
8
10
12
14
16
1
3
5

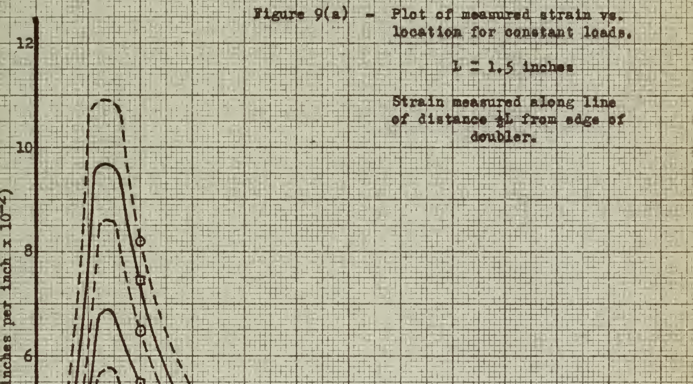
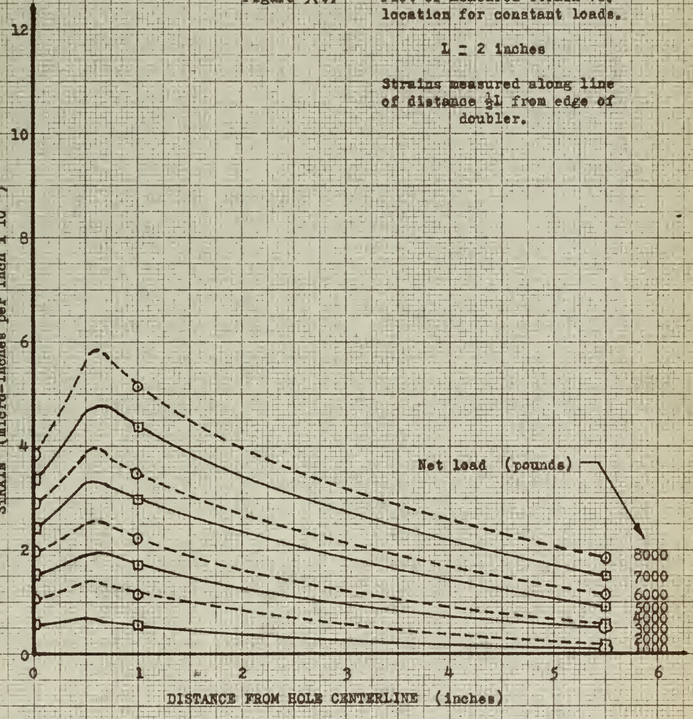


Figure 9(a) - Plot of measured strain vs. location for constant loads.
L = 1.5 inches
Strain measured along line of distance ½L from edge of doubler.
Net load (pounds)
8000
7000
6000
5000
4000
3000
2000
1000
STRAIN (micro-inches per inch x 10⁻²)
DISTANCE FROM HOLE CENTER LINE (inches)
0
2
4
6
8
10
12
1
3
5

Figure 9(b) - Plot of measured strain vs. location for constant loads.

L = 2 inches

Strains measured along line of distance $\frac{1}{2}L$ from edge of doubler.



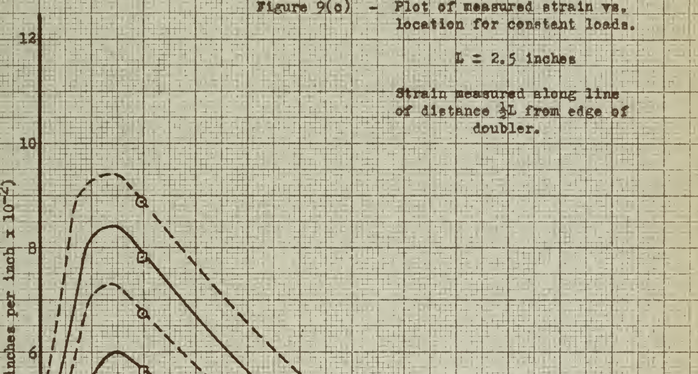


Figure 9(c) - Plot of measured strain vs. location for constant loads.
L = 2.5 inches
Strain measured along line of distance ½L from edge of doubler.
STRAIN (micro-inches per inch x 10^-2)
12
10
8
6
4
2
0
Net load (pounds)
8000
7000
6000
5000
4000
3000
2000
1000
0
1
2
3
4
5
6
DISTANCE FROM HOLE CENTERLINE (inches)

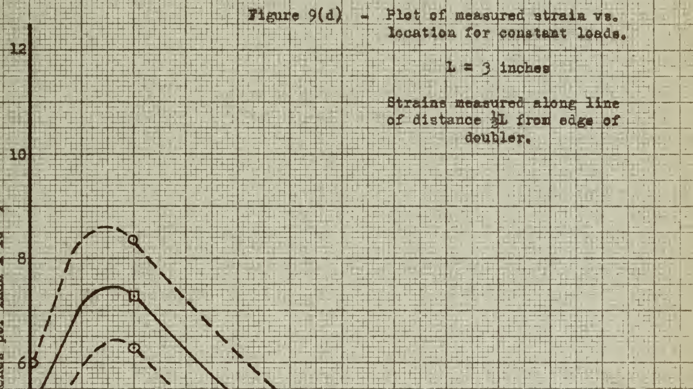


Figure 9(d) - Plot of measured strain vs. location for constant loads.
L = 3 inches
Strains measured along line of distance ½L from edge of doubler.
Net load (pounds)
8000
7000
6000
5000
4000
3000
2000
1000
STRAIN (micro-inches per inch x 10^{-2})
0
2
4
6
8
10
12
0
1
2
3
4
5
6
DISTANCE FROM HOLE CENTERLINE (inches)

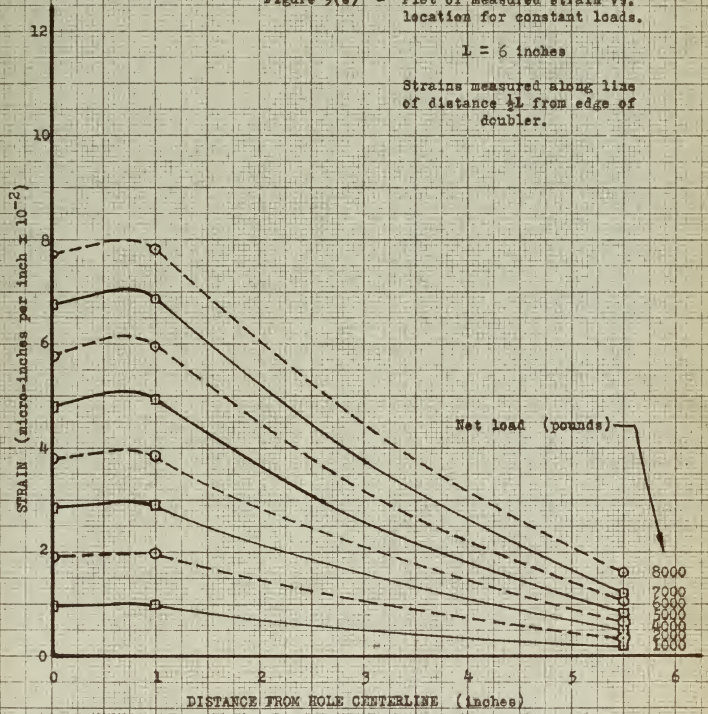


Figure 9(e) - Plot of measured strain vs. location for constant loads.

L = 6 inches

Strains measured along line of distance $\frac{1}{2}$L from edge of doubler.

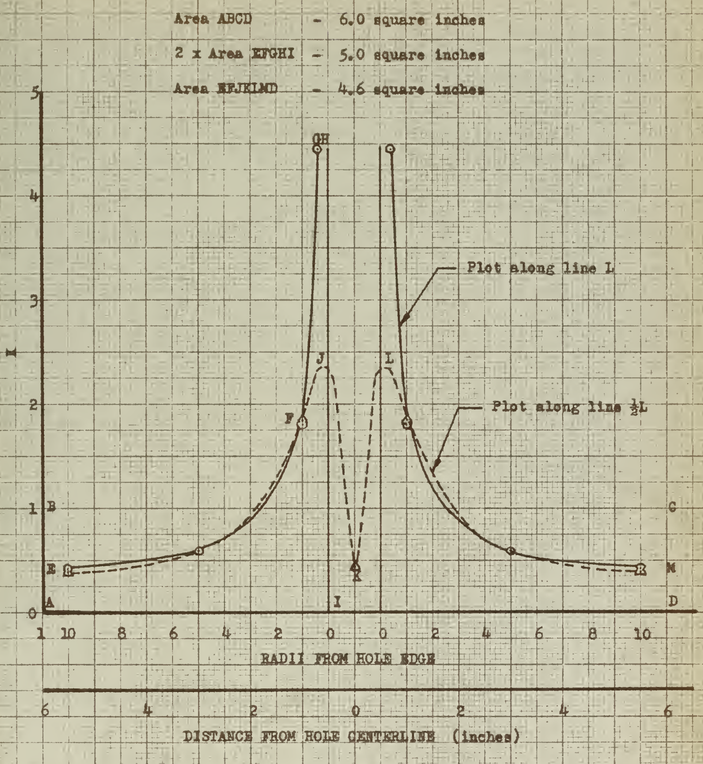


Figure 10(a) - Plot showing the effect of lateral location on the ratio of actual p_1 to theoretical p_1. Plots made along line L and along line $\frac{1}{2}$L.
8000 pounds net load.
L = 1.5 inches.

Area ABCD - 6.0 square inches

2 x Area EFGHI - 5.1 square inches

Area EFJKLMD - 3.5 square inches

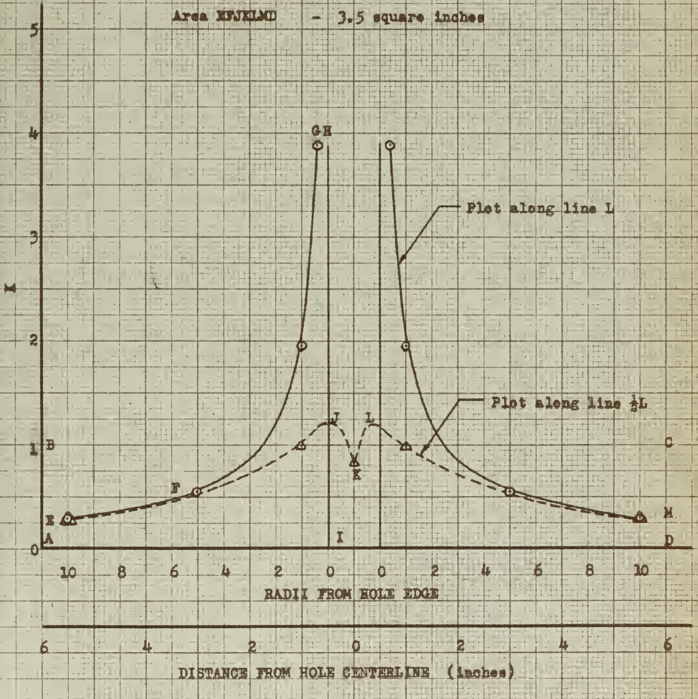


Figure 10(b) - Plot showing the effect of lateral location on the ratio of actual p_1 to theoretical p_1. Plots made along line L and along line $\frac{1}{2}$L. 8000 pounds net load. L = 2 inches.

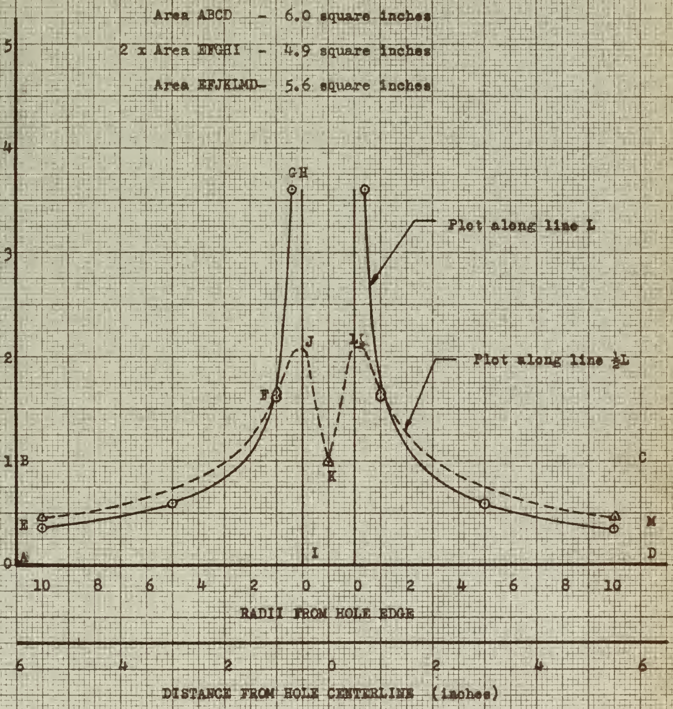


Figure 10(c) - Plot showing the effect of lateral location on the ratio of actual p_1 to theoretical p_1. Plots made along line L and along line ½L.
8000 pounds net load.
L = 2.5 inches.

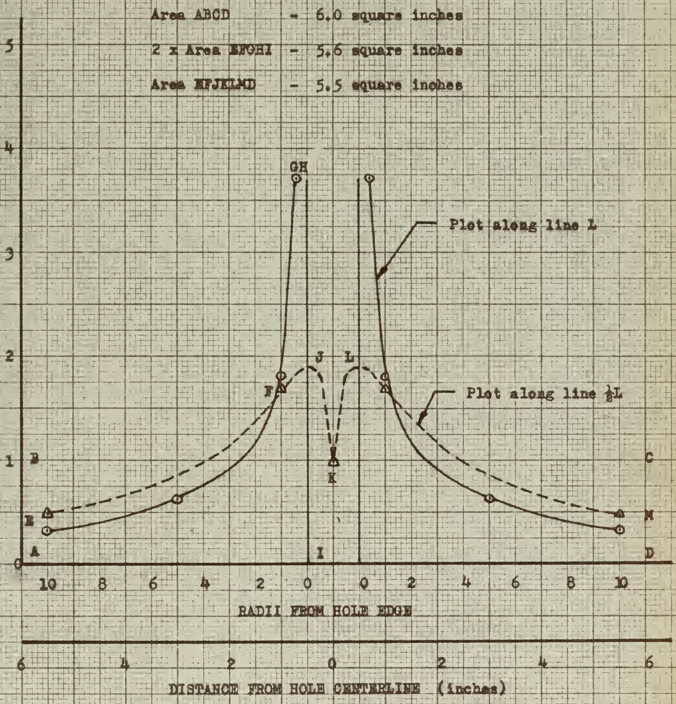


Figure 10(d) - Plot showing the effect of lateral location on the ratio of actual p_1 to theoretical p_1. Plots made along line L and along line ½L. 8000 pounds net load. L = 3 inches.

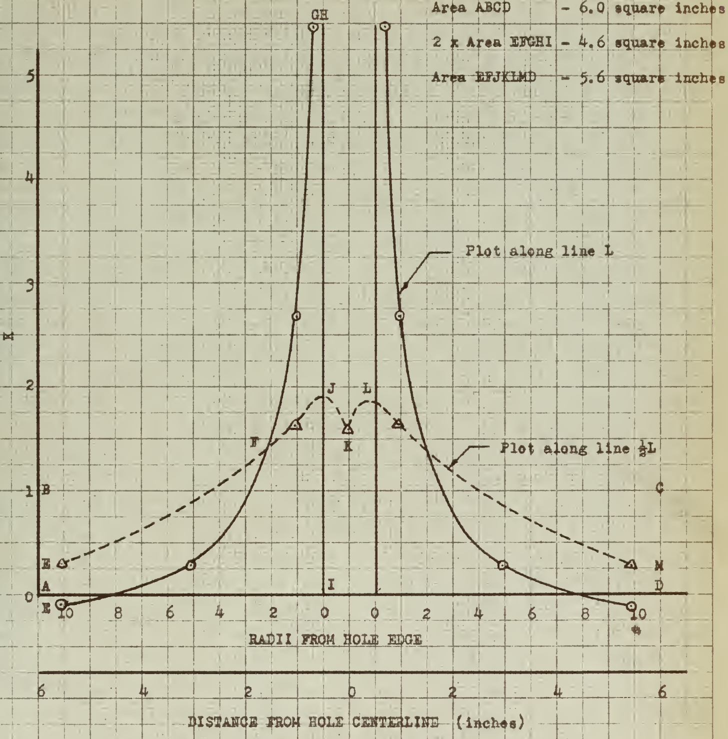


Figure 10(e) - Plot showing the effect of lateral location on the ratio of actual p_1 to theoretical p_1. Plots made along line L and along line ½L.
8000 pounds net load.
L = 6 inches.

Date Due